Reduction of common mode voltage for grid-connected multilevel inverters using fuzzy logic controller

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ABSTRACT

Cascaded multilevel three-phase inverters are increasing in industries of electric drives and renewable energy because of their large capacity and suffering from high voltage shock. However, the high magnitude of common mode voltage is one of the drawbacks. Thus, the techniques of modulation and control in these multilevel inverters significantly affect the power quality of the output voltage of inverters. This paper presents a technique using fuzzy logic technique for grid-connected cascaded multilevel 3-phase inverters. This technique has completely removed the current controllers and the conventional modulation using carriers. It also helps reduce the magnitude of common mode voltage and increase the dynamic response. Moreover, the ability to reduce harmonics and switching count also helps decrease the switching loss of inverter. The simulation results on a grid-connected cascaded 5-level 3-phase inverter have validated the effectiveness of the presented technique compared with that of the conventional method using phase opposition disposition (POD) and PI current controllers.

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1. INTRODUCTION

Cascaded multilevel three-phase inverters are increasing [1]–[8] in industries of renewable energy and electric drives [4], [9]–[13] due to their advantages such as high power capacity, the ability to provide a output voltage similar to sinusoidal waveform [14], and suffer from high voltage shock. Factors significantly affect the inverter output voltage quality consisting of the modulation method, current controllers, and phase-locked loop (PLL). Many modulation solutions have been published. However, in most these solutions, the modulated signals are directly compared with the carriers [15]–[19]. The common mode voltage (CMV) of the cascaded multilevel 3-phase inverter (CM3I) is one of the factors that need to be considered. The high magnitude of CMV negatively impacts the operation of three-phase electric motors by causing high-frequency disturbances and leakage currents [20], [21]. In grid-connected CM3I systems powered by renewable energies, the CMV generates leakage currents and injects harmonic currents into the grid [22]. Thus, there are various solutions [23]–[30] to improve the output power quality of inverters through reduced-common-mode voltage strategies. However, increasing the carrier wave frequency to reduce harmonics leads to larger memory size and higher switching count, causing increased switching loss. This also causes the switching loss to increase. While the CMV magnitude of grid-connected multilevel inverters in [31]–[33] has not been considered and evaluated quantitatively.

The fuzzy logic method has been applied in many fields of control [34]–[38]. However, in grid-connected CM3Is, it still exists some problems such as using the carrier waves for modulating and the PI current controllers for controlling [33]. These cause the dynamic response to decrease and the over-

shoot/under-shoot to increase. In addition, the CMV and number of switching commutations have not been considered and evaluated quantitatively. This paper proposes a method using fuzzy logic technique to control the grid-connected CM3Is. In the proposed method, the modulation does not use the carriers and the PI current controllers are removed completely. Moreover, the PLL does not exist anymore. As a result, it helps reduce the magnitude of CMV and increase the dynamic response. In addition, the results of the proposed technique are also compared with those of the conventional method using phase opposition disposition (POD) and PI current controllers. The validity of the performance has also been established basing on simulation results. A model of grid-connected cascaded H-bridge 5-level 3-phase inverter is shown in section 2. The approach method of PI current controllers and POD modulation is also presented in this section. The fuzzy logic method is presented in section 3. The simulation results for the conventional method using PI current controllers combined with POD and the proposed method using the fuzzy logic technique are shown in section 4 with different values of reference powers. In section 5, the results are discussed and the conclusion of the presented fuzzy logic technique's effectiveness is reached.

2. GRID-CONNECTED CASCADED 5-LEVEL 3-PHASE INVERTER SYSTEM

The structure of a grid-connected cascaded H-bridge 5-level three-phase inverter system is described in Figure 1. In this system, the PLL, PI controllers, and the POD modulation are used for controlling the currents injected into the grid based on the reference powers P_{ref} and Q_{ref}. Where the PLL is used to estimate the angular frequency ω of the grid voltage for synchronization via the current controllers.

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos(\omega t) & cos\left(\omega t - \frac{2\pi}{3}\right) & cos\left(\omega t + \frac{2\pi}{3}\right) \\ -sin(\omega t) & -sin\left(\omega t - \frac{2\pi}{3}\right) & -sin\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix}\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} I_\alpha^* \\ I_\beta^* \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2}\begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix}\begin{bmatrix} P_{\mathrm{ref}} \\ Q_{ref} \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} I_d^* \\ I_q^* \end{bmatrix} = \begin{bmatrix} cos(\omega t) & sin(\omega t) \\ -sin(\omega t) & cos(\omega t) \end{bmatrix}\begin{bmatrix} I_\alpha^* \\ I_\beta^* \end{bmatrix} \tag{4}$$

$$G_{PI}(s) = \begin{bmatrix} K_p + \frac{K_i}{s} & 0 \\ 0 & K_p + \frac{K_i}{s} \end{bmatrix} \tag{5}$$

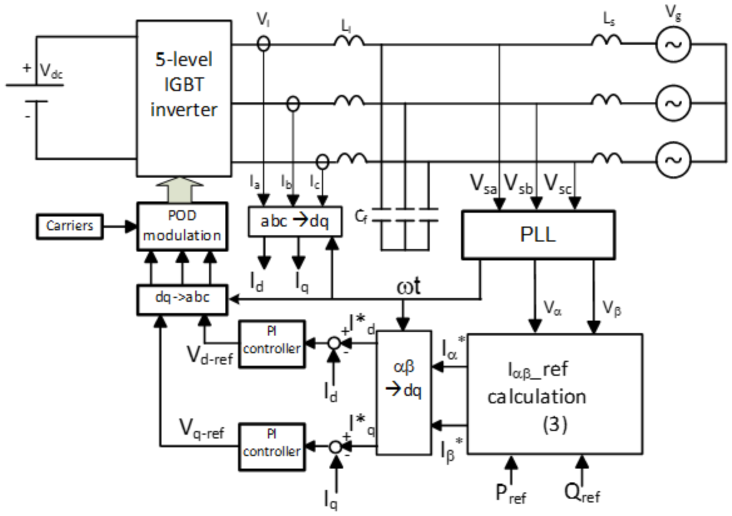


Figure 1. Principle diagram of a grid-connected three-phase inverter system

The phase angular ωt is estimated by the PLL technique [39]–[41] and used for transformations in (1) and (4). The voltages V_α and V_β are defined as (2) and used to calculate the reference currents I_α_ref and I_β_ref as (3) basing on the reference powers. In grid-connected inverters, the PI controllers are usually used and their transfer functions as (5). Where Kp and Ki are the coefficients of the PI controllers. Then, the structure of these current controllers is also shown in Figure 2 and the POD modulation uses a control principle in Figure 3. The main circuit of one phase consists of two H bridges using IGBTs as shown in Figure 4. Where Sxj represents the ON/OFF state of the respective switches as (6), with the phases x = a, b, c. The H-bridge's top and bottom switches are represented by Sxj1 and Sxj2, respectively.

$$Sxj1 + Sxj2 = 1;\ \text{with } j = 1 \div 4 \tag{6}$$

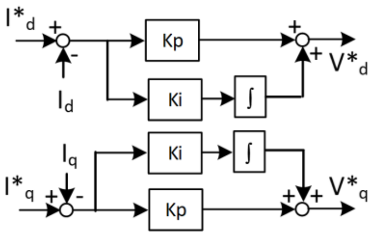


Figure 2. Proportional integral controllers

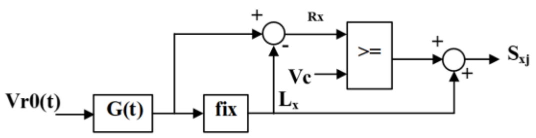


Figure 3. Inverter control diagram

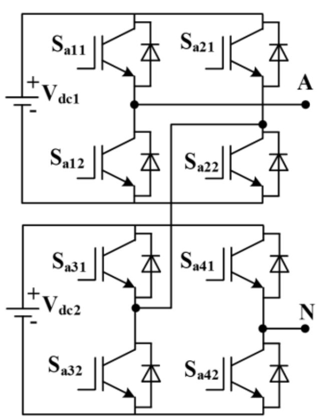


Figure 4. Main circuit diagram of phase A

The switching states of transistors of one phase are shown in Table 1. Where n = 5 is the level number of inverters and the voltages of dc sources have the same values, 5 levels of output voltage are -2Vdc, -1Vdc, 0, +1Vdc, and +2Vdc respectively. The inverter control scheme depicted in Figure 3 utilizes Vr0, a control signal with a magnitude ranging from -1 to +1, and G(t), a signal normalized to the inverter levels defined in (7). Vc is the carrier and Sxj is the state of switches described in Table 1.

$$G(t) = (\mathrm{Vr0}(t) + 1)\frac{\mathrm{n-1}}{2} \tag{7}$$

$$L_x = \begin{cases} \mathrm{n-2}, & \text{if} G(t) \geq \mathrm{n-2} \\ \mathrm{fix}(G(t)), & \text{otherwise} \end{cases} \tag{8}$$

$$\mathrm{CMV} = \frac{V_a + V_b + V_c}{3} \tag{9}$$

Table 1. Phase A switching states of switches

n	Sa1	Sa2	Sa3	Sa4	Output voltage
1	0	1	0	1	-2 Vdc
2	0	1	0	0	-Vdc
3	0	0	0	0	0
4	1	0	0	0	+Vdc
5	1	0	1	0	+2 Vdc

In the control diagram, R_x and L_x are the two components of the voltage G(t), (x = a, b, c). Where $0 \leq L_x \leq n-2$ is the integer of the signal G(t) and calculated as (8) and $0 \leq R_x \leq 1$ is the remainder after division. The modulation technique POD using carriers for a 5-level inverter is also shown in Figure 5. Where the control signal G(t) has a fundamental frequency of 50 Hz and the carrier has a frequency of 2 kHz. The POD modulation method of 5-level inverter gives the common mode voltage CMV as (9) and as $V_{dc}/3$. These voltage waveforms V_x are measured at the inverter output.

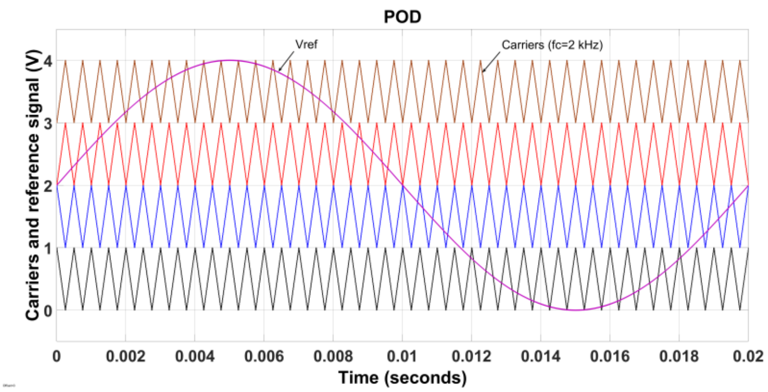


Figure 5. POD modulation method

3. PROPOSED FUZZY LOGIC METHOD

The structure of the proposed method using fuzzy logic controller is shown in Figure 6. The reference phase currents are defined as (10). The principle of the proposed method is also described in Figure 7.

$$\begin{bmatrix} I *_a \\ I *_b \\ I *_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} I *_\alpha \\ I *_\beta \end{bmatrix} \tag{10}$$

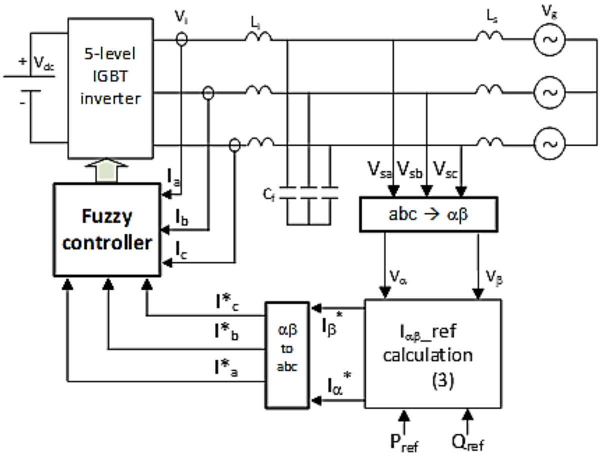


Figure 6. Principle diagram of grid-connected inverter system using fuzzy logic technique

The fuzzy rules are described as Table 2. The input signals consist of two components, e and de as Figure 8. Where e is the error between the reference currents and the currents measured at the inverter output, and de is the derivative of error. e and de are used as the inputs of the fuzzy block in Figure 7. The output of the fuzzy block V_f is the voltage levels v_i. The voltage levels of V_f are filtered by a low-pass filter before taking into the normalization block G(t) to obtain the signal from 0 to 4. In the modulation method, a voltage constant C is used for comparing with the signal R_x. The value C can vary from 0.45 to 0.55 depending on the balance between the switching count and harmonic. In addition, an offset function R_0 proposed in [42], [43] is also used to subtract from this constant. Therefore, this system does not use carriers.

Table 2. Fuzzy rules of output

		e		
		SE	ME	LE
de	SD	v_1	v_4	v_7
	MD	v_2	v_5	v_8
	LD	v_3	v_6	v_9

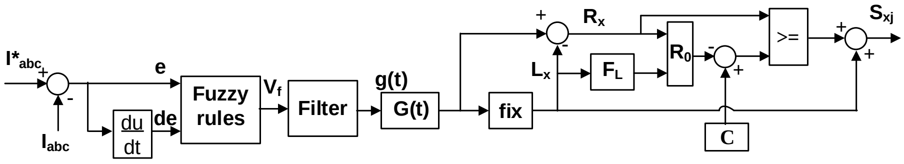


Figure 7. Proposed fuzzy controller

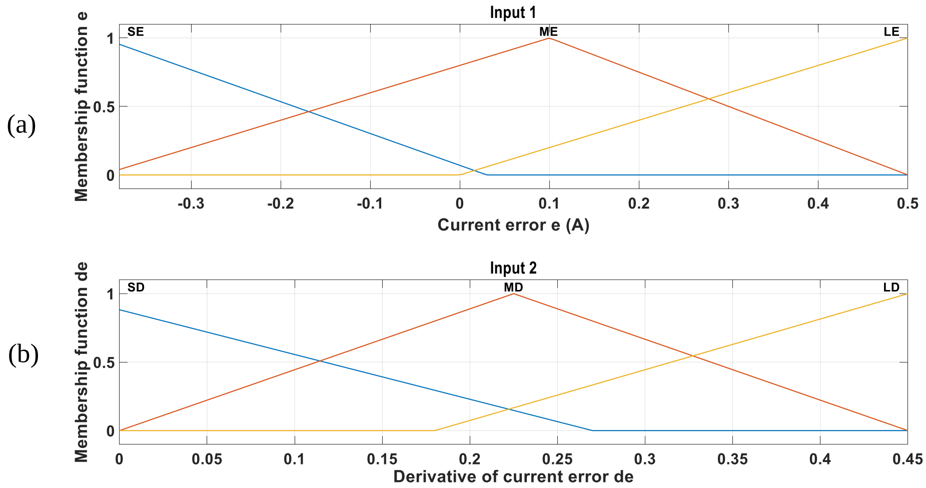


Figure 8. Inputs of fuzzy controller (a) input 1 and (b) input 2

4. RESULTS AND DISCUSSION

The parameters for simulation system are shown in Table 3 with the step change of reference powers in Figure 9 in three intervals of time, 0-0.3 s, 0.3-0.6 s, and 0.6-0.9 s. The two method results are shown in Figures 10-14. The voltage waveforms in Figures 10 and 11 showed the CMV of proposed fuzzy method is equal to that of the PI-POD method and as $V_{dc}/3$. However, the switching count of the fuzzy technique is less than that in Figure 12 of the PI-POD method. In addition, the phase current THD values of the proposed method in Figures 13(d)-13(f), as 3.08%, 5.88%, and 5.37%, are also lower than those of the PI-POD method in Figures 13(a)-13(c), as 3.34%, 7.17%, and 5.77% respectively. Moreover, the magnitudes of individual harmonic in PI-POD method in Figures 13(a)-13(c), up to 2.05%, 4.2%, and 3.3%, are always higher those of the fuzzy method in Figures 13(d)-13(f), only as 1.4%, 3.05%, and 2.2% respectively. This also helps the power ripples injected into the grid of the proposed method in Figure 14 less than those of the PI-POD method. The power responses in Figures 14(a) and 14(b) also showed that the fuzzy method offers better dynamics and smaller over-shoots/under-shoots.

Table 3. System parameters

Description	Value
Grid source voltage	3*380 V
Grid fundamental frequency f	50 Hz
Grid source resistor and inductor R_s, L_s	0.01 Ω, 0.1 mH
Resistor and inductor of filter R_i, L_i	0.01 Ω, 3 mH
Capacitor of filter C_f	1 micro Fara
DC voltage Vdc	160 V
Coefficients of PI controller Kp, Ki	0.15, 20
Carrier frequency of POD f_c	2 kHz
Rated reference active power Pref	20 kW
Rated reference reactive power Qref	5 kVar
Time constant of low-pass filter	0.2 ms
Constant C	0.5

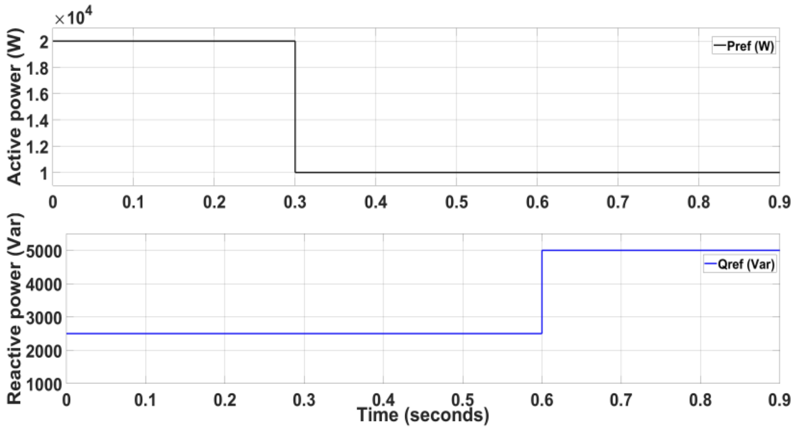


Figure 9. Reference powers

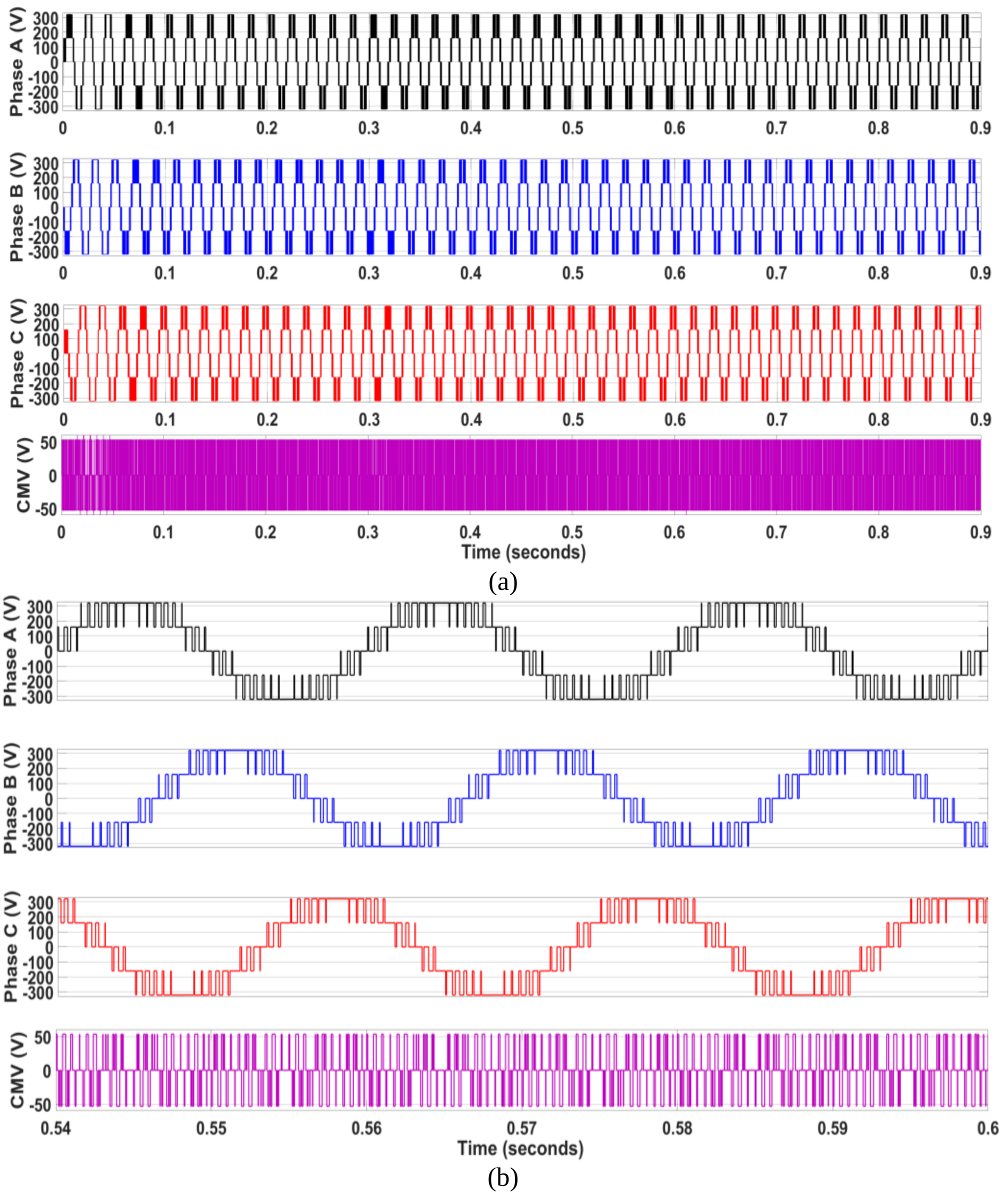


Figure 10. Phase voltages and CMV of POD (a) waveforms and (b) waveforms zoomed in 0.54-0.6 s

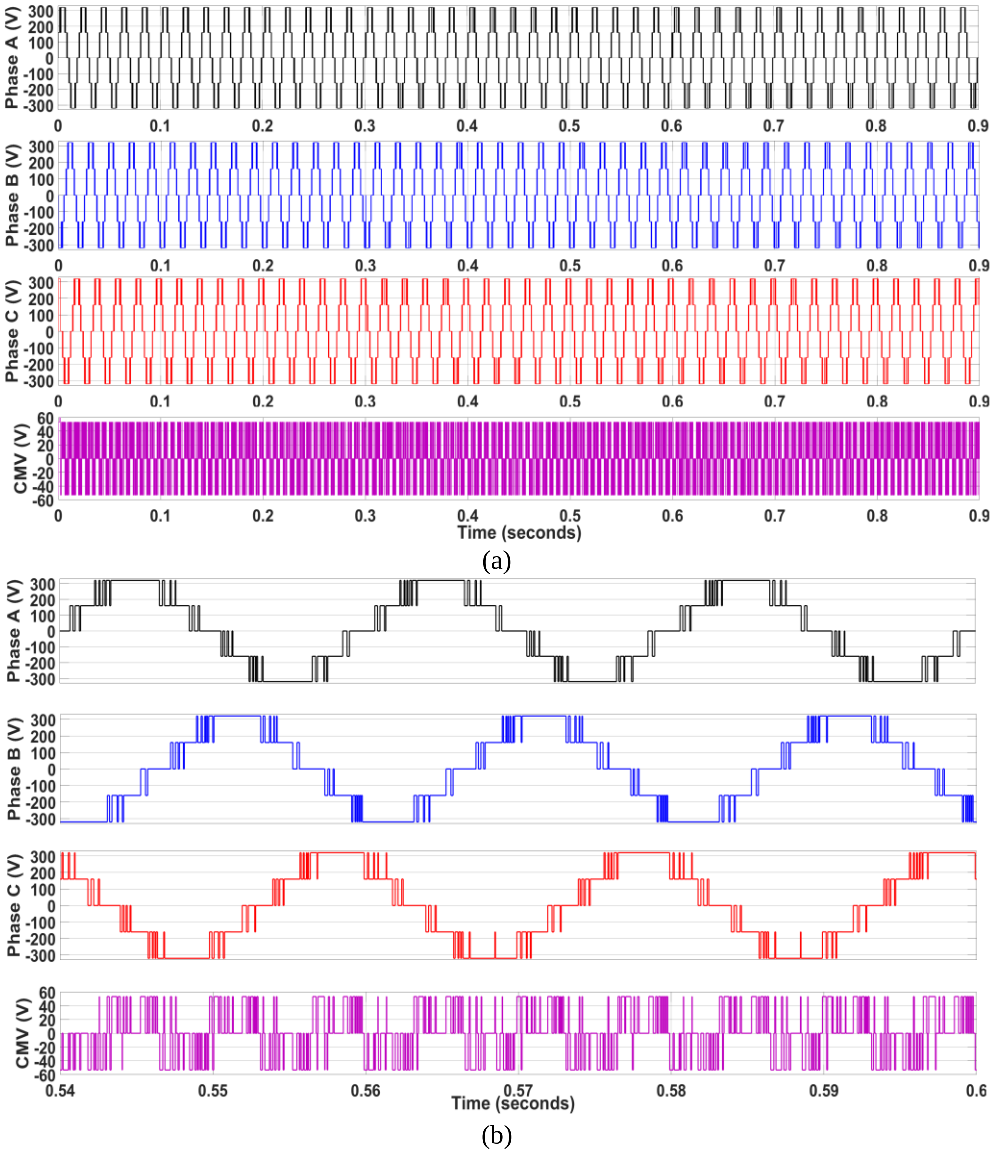


Figure 11. Phase voltage and CMV of fuzzy method (a) waveforms and (b) waveforms zoomed in 0.54-0.6 s

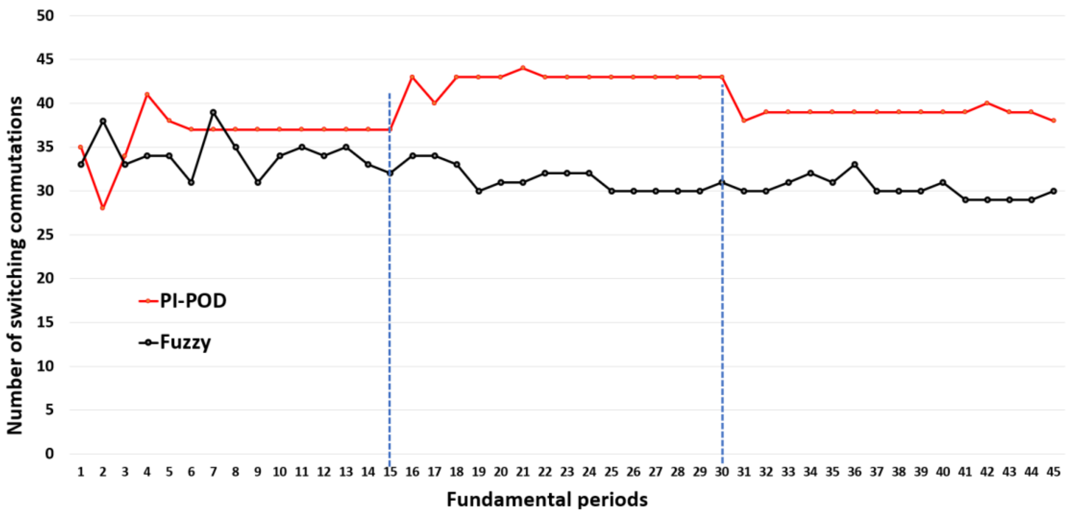


Figure 12. The number of commutations in fundamental periods

(f)

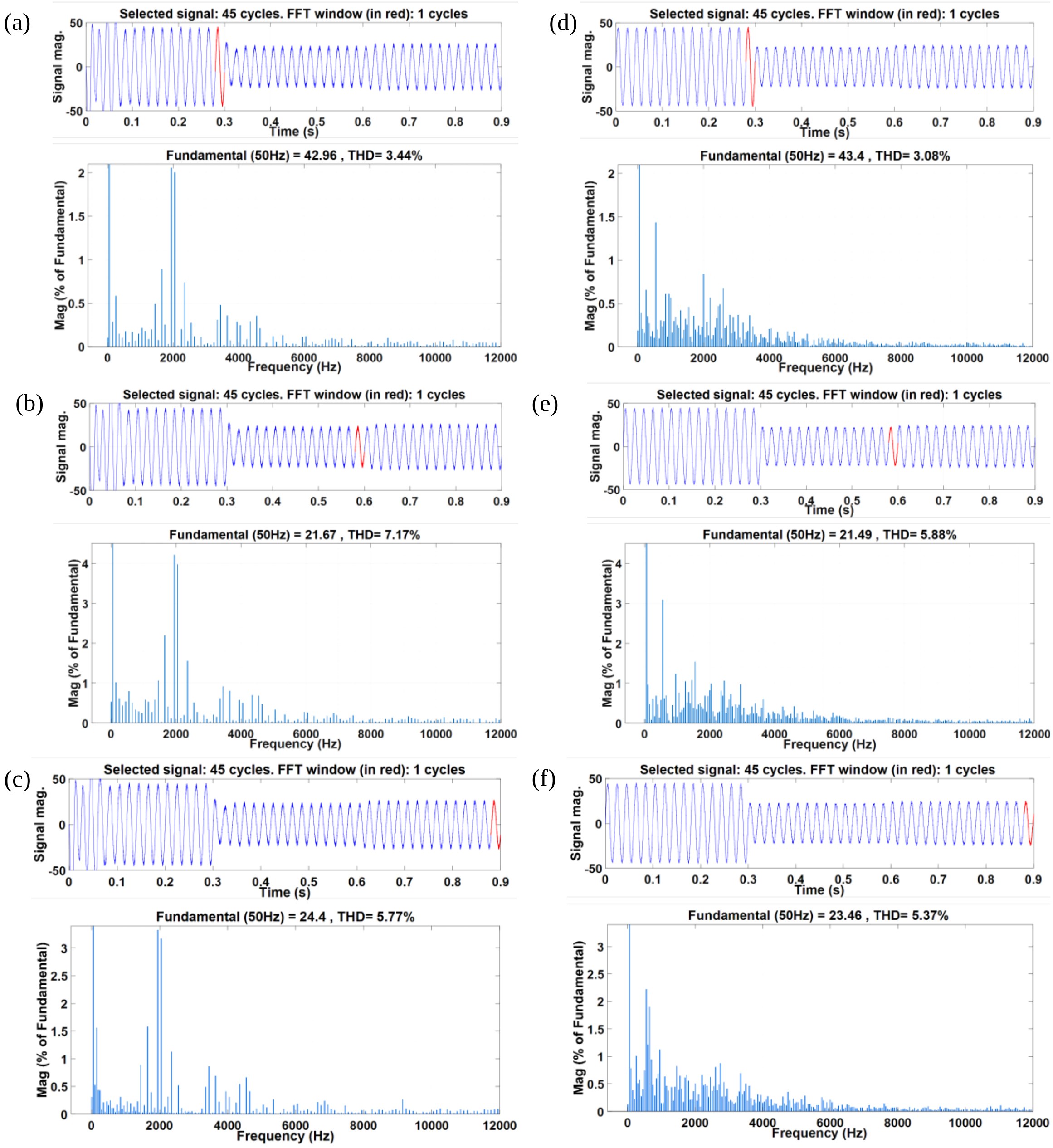
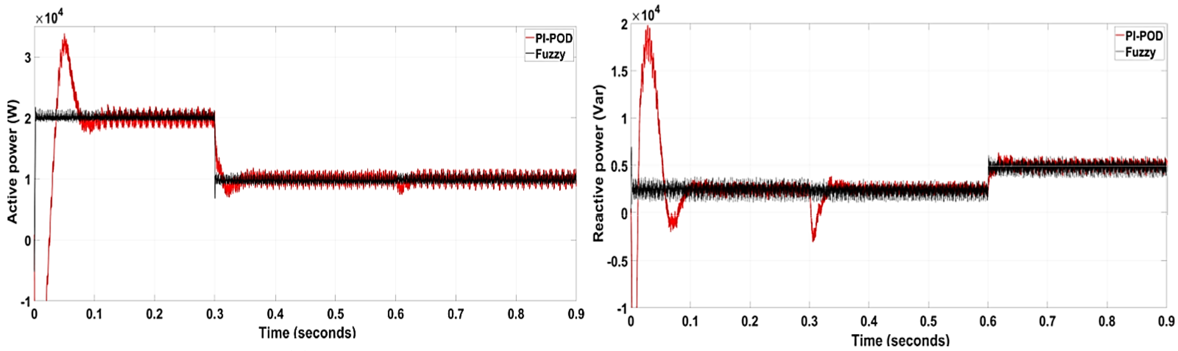


Figure 13. Spectrum of phase current A injected into the grid (a)-(c) POD method and (d)-(f) fuzzy method



(a) (b)

Figure 14. Power responses injected into the grid (a) active powers and (b) reactive powers

5. CONCLUSION

This paper has proposed a technique for controlling the grid-connected CM3Is using fuzzy logic technique to reduce the CMV. This technique also helps the CM3Is reduce the switching count and the current harmonics injected into the grid. The proposed method does not use carriers, the PI current controllers, and PLL. This can provide a better dynamic response. The simulation results have confirmed the effectiveness of the proposed method in the grid-connected system of cascaded 5-level 3-phase inverter compared with that of the method using carriers of POD and the PI current controllers.

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